TECHNICAL/BUDGET

Introduction

The Voyager Interstellar Mission (VIM) is an extension of the Voyager planetary exploration mission that was completed in 1989 after the two Voyagers had completed their planned flybys of the Jupiter, Saturn, Uranus and Neptune planetary systems. At the start of the VIM, the two Voyager spacecraft had already been in flight for over twelve years, having successfully returned a wealth of scientific information about the giant gaseous planets and the interplanetary medium between Earth and Neptune. Since 1989 the Voyagers have been characterizing the interplanetary medium beyond Neptune while they search for the transition region between the interplanetary and interstellar media. Passage through the termination shock begins the journey through the transition region, the heliosheath.

Voyager 1 is escaping the solar system at a speed of about 3.6 AU per year while Voyager 2 is leaving at about 3.3 AU per year. Power is the limiting lifetime consumable. The two spacecraft have power to continue returning science data until around the year 2020. All other consumables are adequate.

The Voyager Spacecraft

Voyager spacecraft subsystems and instruments required for the interstellar mission are operating well and are fully capable of supporting the science mission through 2020.

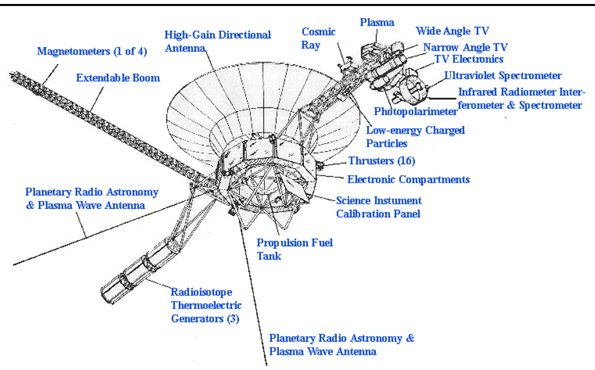

FIGURE A: The Voyager Spacecraft

The identical Voyager spacecraft (Figure A) are three-axis stabilized systems that use celestial or gyro referenced attitude control to maintain pointing of the high-gain antennas toward Earth. The prime mission science payload consisted of 10 instruments (11 investigations including radio science). Only five investigator teams are still supported, though data are collected for two additional instruments, the Planetary Radio Astronomy (PRA) instrument and the Ultraviolet Spectrometer (UVS). Active teams and the status of their instruments are: described in Table 1.

Investigator Teams	**Principal*** and Co-Investigators	Instrument Status
Plasma Science (PLS)	**J.D. Richardson*** J. W. Belcher L.F. Burlaga A.J. Lazarus K.W. Ogilvie E.C. Sittler, Jr. C. Wang	Instrument performing normally on Voyager 2. Voyager 1 ion data not useable
Low-Energy Charged Particles (LECP)	**S.M. Krimigis*** T.P. Armstrong R.B. Decker G. Gloeckler D.C. Hamilton W-H. Ip E.P. Keath L.J. Lanzerotti B.H. Mauk R. McNutt	Instruments performing normally on both spacecraft
Cosmic Ray Sub-system (CRS)	**E.C. Stone*** A.C. Cummings N. Lal F.B. McDonald W.R. Webber	Except for one of four low-energy telescopes on Voyager 2, instruments performing normally on both spacecraft
Magnetometer (MAG)	**N.F. Ness*** M. Acuña L.F. Burlaga C. Smith F.M. Neubauer	Instruments performing normally on both spacecraft though magnetic field intensity levels are lowest ever measured
Plasma Wave Subsystem (PWS)	**D.A. Gurnett*** W.S. Kurth	Voyager 1 instrument performing normally. Voyager 2 wideband receiver sensitivity level is low and high rate data no longer usable.

Table 1: Voyager Investigations and Status

The entire Voyager 2 scan platform, including all of the platform instruments, was powered down in 1998. All platform instruments on Voyager 1, save the UVS, have been powered down. The Voyager 1 scan platform was scheduled to go off-line in late 2000, but has been left on at the request of the UVS investigator (with the concurrence of the Science Steering Group) to investigate an unexpected excess in UV from the upwind direction. The PLS experiment on Voyager 1 is currently turned off to accommodate UVS observations, but is planned to be turned on when there is evidence that the spacecraft is in the vicinity of the termination shock. Voyager 1 scan platform and the UVS instrument will be reconfigured within a year because of power conservation considerations. In the reconfigured state, a capability will remain to take data but the full range of scans will no longer be possible.

The Flight Data Subsystem (FDS) and a single 8-track digital tape recorder (DTR) provide the data handling functions. The FDS configures each instrument and controls instrument operations. It also collects engineering and science data and formats the data for transmission. The DTR is used to record high-rate PWS data. Data are played back every six months. The FDS and DTR continue to perform normally.

The command computer subsystem (CCS) provides sequencing and control functions. The CCS contains fixed routines such as command decoding and fault detection and corrective routines, antenna pointing information, and spacecraft sequencing information. The CCS on both spacecraft are performing normally.

The Attitude and Articulation Control Subsystem (AACS) controls spacecraft orientation, maintains the pointing of the high gain antenna towards Earth, controls attitude maneuvers, and positions the scan platform. Voyager 2 pitch/yaw thrusters were swapped to an alternate branch in 1999 by fault protection software due to a yaw plumbing failure. After noticing a similar trend on Voyager 1, the Spacecraft Team made a similar switch via a mini-sequence. Gradual degradation of the analog to digital (A-D) converter in the Hybrid Buffer Interface Circuit (HYBIC) on Voyager 1 culminated in a slew abort in late 2001. In March 2002, a switch was made to the redundant HYBIC, which has been performing like new since that time. After more than a year of operation, the prognosis is good for continued operations through 2020. The degraded hardware is expected to be usable as a spare in case the fault protection system switches over to it.

Uplink communication is via S-band (16-bits/sec command rate) while an X-band transmitter provides downlink telemetry at 160 bits/sec normally and 1.4 kbps for playback of high-rate plasma wave data. All data are transmitted from and received at the spacecraft via the 3.7 meter high-gain antenna (HGA). Failure of Receiver 1 on Voyager 2 in 1978 leaves the spacecraft with no backup receiver and, because of an earlier failure of the Tracking Loop Capacitor in Receiver 2, the acquisition frequency bandwidth was drastically reduced. This necessitates the routine use of special procedures to uplink at the best lock frequency. Voyager 2 is currently operating on the alternate transmitter following an autonomous switch in 1998. The project has elected to remain on the currently selected transmitter. Telecommunications with both spacecraft are normal and the link margins are sufficient to maintain two-way contact with the spacecraft past 2020.

Electrical power is supplied by three Radioisotope Thermoelectric Generators (RTGs). The current power levels are about 306 watts for each spacecraft. As the electrical power decreases, power loads on the spacecraft must be turned off in order to avoid having demand exceed supply. As loads are turned off, spacecraft capabilities are eliminated. The RTGs are performing normally. Average degradation rate is about 4.7 watts per year. Power margins are adequate to operate the spacecraft science instruments until about 2020.

Operations Concept

The Voyager Interstellar Mission is characterized by (1) science requirements that can be satisfied with science instrument observations that are primarily repetitive in nature, and (2) long communication distances and the resulting long round-trip-light-times which limit spacecraft monitoring and control.

In addition, programmatic changes since the beginning of the VIM have significantly reduced flight team staffing levels. As opposed to a group of specialists, as it was earlier in the mission, each member of the current flight team performs multiple functions and only limited backup capability exists.

These mission characteristics and the small team size have resulted in the evolution to the current methods used to conduct mission operations. The ground telemetry and command systems have transitioned from project dedicated hardware and software to multi-mission systems. The sequence generation process has evolved to one consistent with the repetitive nature of the science observations. Changes have been made to the process for real-time monitoring of routine spacecraft operations and an automated alarm-monitoring tool was developed. Each of these is discussed further in the following sections.

The mission impact of the reduced staffing includes reduced operational flexibility, reduced anomaly response capability, a slight reduction in science data acquisition, and potential delays in science data delivery. In addition, many lower priority tasks may not be performed.

Sequence Generation

Key to acquiring the desired science observations and maintaining an adequate level of mission adaptivity is the sequencing strategy. Because of the limited flight team resources available for spacecraft sequence generation, this strategy has to minimize the labor required while satisfying the science data acquisition requirements and flight system health and safety engineering needs.

The sequencing strategy is composed of four basic elements. First is a continuously executing sequence of repetitive science observations and engineering calibrations called the "baseline sequence." A baseline sequence is stored on-board each spacecraft and contains the instructions needed to acquire and return the basic fields, particles, and waves science data to the ground. This sequence will continue to execute for the duration of the mission.

The second element is the storage on-board each spacecraft of the pointing information necessary to keep the boresight of the High Gain Antenna (HGA) pointed at the Earth. Data until the year 2020 is stored on Voyager 1 and until 2017 on Voyager 2. This provides the capability for continuous communication with each spacecraft without further HGA pointing commands.

The third element provides the capability of augmenting the baseline sequence with non-repetitive science or engineering events using either an "overlay sequence," or a "mini-sequence." The difference between these two types of augmentation sequences is that the overlay sequence operates for a fixed interval of time, currently 3 months, and contains all of the baseline sequence augmentations for that time interval. A mini-sequence is focused on accomplishing a single augmentation need and is not a regularly scheduled activity but is done on an as-needed basis.

The fourth element is the use of pre-defined and validated blocks of commands (high level sequencing language), rather than the optimized sequence of individual commands (low level sequencing language) used during the prime mission, to accomplish desired spacecraft functions. While the use of pre-defined blocks of commands greatly reduces the effort required to generate and validate a sequence of commands, there is sometimes inefficiency in the number of memory words needed to accomplish a given function. Fortunately, the VIM science data acquisition requirements and available on-board sequence storage memory support the use of pre-defined blocks of commands.

Transmitting the Data to the Ground

The Voyager Interstellar Mission is, with one exception, a real-time data acquisition and return mission. All of the operating instruments on each spacecraft are continuously collecting data and transferring it to the FDS for immediate transmission to Earth. The normal real-time transmission data rate is 160 bits per second (bps), including 10 bps engineering data. Periodically the real-time data rate is increased to 600 bps to provide increased ultraviolet spectral resolution.

The one exception to real time data return is that once a week, 48 seconds of high rate (115.2 kbps) plasma wave data are recorded onto the DTR. These data are played back every 6 months and provide increased spectral resolution snapshots of the plasma wave information. These high rate plasma wave data have provided the primary data for the Plasma Wave Investigation Team's estimate of the termination shock and heliopause locations. The current DTR playback data rate is 1.4 kbps. Recording and playback of high rate plasma wave data can continue until the years 2010 (Voyager 1) when telecommunications capability will no longer support the minimum playback data rate of 1.4 kbps. No special effort will be made to playback Voyager 2 data.

Capturing the Data on the Ground

Real-time telemetry data capture is accomplished using 34- and 70-meter tracking antennas of the DSN. Capture of the recorded high rate plasma wave data requires the use of 70 meter tracking antennas.

Sixteen hours per day of tracking support for each spacecraft is the project's target for science data acquisition, particularly in the vicinity of the termination shock. Because Voyager is not a high priority mission, it is usually allocated support after higher priority mission requirements have been satisfied. In the recent past, the average daily support has been about 8-12 hours. Future increases in missions being supported by the DSN stations will result in reduced tracking station availability for the two Voyager spacecraft. As tracking support is reduced, the ability to characterize the heliospheric medium is degraded. Acceptable minimum science data acquisition requirements range from 4 to 12 hours per day per spacecraft on average, depending on the specific investigation.

Delivery to Science Investigation Teams

Science data are provided electronically to the science investigation teams in the form of a Quick Look Experiment Data Record (QEDR) and Experiment Data Record (EDR). A Voyager 1 and Voyager 2 QEDRs for each science investigation are generated daily (Monday through Friday) containing the available data since the last QEDR was produced. Since these products are produced in near real-time, generally within 24 hours of the data capture, data gaps due to a variety of ground system problems can be present in the QEDR. Once a week, EDRs are created for the previous week's data. In this product, data gaps resulting from ground problems have been filled to the extent possible. When the final EDRs are available, science teams are notified by electronic mail. The science teams then retrieve the data at their convenience for further processing and analysis.

Spacecraft Monitor and Control

Spacecraft monitor and control includes the real-time functions necessary to monitor spacecraft health and to transmit and verify commands. During the primary Voyager mission, flight team personnel supported these real-time functions around the clock. With the reduced flight team staffing during VIM and the acceptability of increased risk during an extended mission, real-time support is limited to weekday prime shift and special off-shift events (commanding, DTR playbacks, and attitude maneuvers). This reduced real-time monitoring support was enabled by the development and implementation of an automated telemetry monitoring tool. This tool, Voyager Alarm Monitor Processor Including Remote Examination (VAMPIRE), processes the broadcast telemetry data, detects alarm conditions, and initiates contact with on-call personnel who may remotely log onto the engineering workstation via a secure dial-back modem to evaluate the telemetry data when potentially anomalous conditions occur. A recent improvement to the VAMPIRE system allows parameters associated with the alarm to be sent via email to email-capable pagers. This automation tool has proved to be valuable in maintaining high mission reliability during significant downsizing of the flight team staffing level.

While spacecraft monitor and control is a real-time operations function, maintaining spacecraft health and safety is a non-real-time function. It includes: the analysis of engineering telemetry data to establish and evaluate subsystem performance trends; the periodic in-flight execution and analysis of subsystem calibrations and engineering tests; analysis of AACS, FDS, and CCS memory readouts; the review and updating of telemetry alarm limits; the identification and analysis of anomalous conditions; and the determination of recommended corrective actions.

The analysis of engineering telemetry data to establish and evaluate subsystem performance trends is a regularly performed operations function. The UNIX workstations provide tabular and graphic summaries of real-time or archived telemetry data. However, the analysis of these data relies on the system and subsystem expertise retained by the individual flight team members. As the flight team loses system and subsystem expertise due to the retirement of experienced personnel and the downsizing of the flight team, the ability to perform trend analysis is adversely impacted.

Periodic in-flight calibrations and engineering tests are used for verifying spacecraft performance, and maintaining spacecraft capabilities. While some of these calibrations and tests are included in the baseline sequence, the majority are initiated from the ground in either an overlay or mini-sequence.

The identification and analysis of anomalous conditions and the determination of recommended corrective actions are functions performed whenever needed. The accomplishment of this is similar to the analysis of engineering telemetry data, in that it relies on the system and subsystem expertise of the individual flight team members. There is an automated tool, Monitor/Analyzer of Real-time Voyager Engineering Link (MARVEL) that monitors CCS/FDS telemetry data to assist the analyst with normal event verification and to display on a workstation screen any conditions that are not as predicted. MARVEL performs limited analysis of the CCS/FDS telemetry and identifies possible causes of the anomalous condition and potential corrective actions from the stored knowledge base within the program.

Protection Against Spacecraft Failures

In order to maximize the spacecraft science data return reliability for a mission that could potentially continue until 2020, automated safeguards against possible mission-catastrophic failures are provided.

Each spacecraft has Fault Protection Algorithms (FPAs) stored on-board that are designed to recover the spacecraft from otherwise mission-catastrophic failures. The FPAs are mostly implemented in the Command Computer System while a few are interactive with the Attitude and Articulation Computer System. The five FPAs stored in the CCS execute pre-programmed recoveries for the following:

- AACS anomalies
- Loss of command reception capability
- Exciter and transmitter hardware anomalies
- CCS hardware and software anomalies
- Anomalous power loads

The second safeguard is the Backup Mission Load (BML), which provides automated on-board protection against the loss of command reception capability. Without command reception capability, the spacecraft must continue to operate with the instructions previously stored in the CCS memory. The BML reconfigures the spacecraft for maximum telecommunications and attitude control reliability and modifies the Baseline Load to continue the acquisition and transmission of fields, particles and waves science data as long as the spacecraft continues to function.

Consumables Management

Both spacecraft have on-board consumables that are adequate to support spacecraft operation until around the year 2020. Hydrazine propellant and electrical power are the two major spacecraft lifetime limiting consumables. Both spacecraft have about 33 kg of hydrazine that provides about 50 years of operation at the current usage rates.

As discussed earlier, electrical power should be adequate until about 2020.

Mission Adaptivity

While Voyager is primarily a non-adaptive real-time data acquisition and return mission, two types of science data acquisition and return adaptivity exist. Both types have been successfully used during VIM.

The first type of adaptivity is the recovery of a high rate PWS playback that is not captured with the initial playback. The response to the loss of a playback is to sequence a second playback prior to the time when data on the DTR is overwritten with newly recorded data. For normal baseline sequence recording of PWS data this allows 6 months to execute a second playback.

The second type of adaptivity is to increase the frequency of high rate PWS recordings and playbacks. This can be in response to a predicted termination shock crossing or increased plasma wave activity during cruise. Increased radio emission activity in 1992 and 1993 resulted in a decision to increase the record and playback frequency to improve the temporal resolution of this observed event. An on-board sequence block that allows increasing the high rate PWS recordings by sending a single command to the spacecraft was designed and now resides in both spacecraft. This block, when activated, will record one PWS frame about every nine hours over a period of two weeks. A second sequence, designed in 2001, is currently being used on Voyager 1 to record one additional frame per week in conjunction with the weekly recording from the baseline load, essentially doubling the amount of recordings over the six-month period before tape recorder readout.

Science Management

The Project Scientist coordinates with the Voyager Science Investigators, the science community, and other elements of the Project to ensure that the Project scientific objectives are met. The Science Steering Group (SSG) is chaired by the Project Scientist and consists of the Principal Investigators for the funded investigations. The SSG has the leading role in the overall optimization of the science return from the mission, and in resolution of conflicting science requirements. Members of the VIM Science Steering Group (the principal investigators) and their co-investigators are listed in Table 1.

Funding for two investigations, the Ultraviolet Spectrometer (UVS) on Voyager 1 and the Planetary Radio Astronomy (PRA) on both spacecraft have been discontinued by NASA; however, both data types are still being received. The UV data are sent to Jay Holberg at the University of Arizona, and the PRA data to Michael Kaiser at GSFC.

The principal investigators, along with their team members, are responsible for analyzing their data and reporting their findings in a timely manner. They participate, as appropriate, in making these results available to the science community and to the general public. They present their results at science conferences, through news releases and via publications in the popular press and scientific journals. A list of both refereed and other papers is available at http://voyager.jpl.nasa.gov/science/bibliography.html

The principal investigators provide archival data to the National Space Science Data Center at Goddard. A summary of data availability and accessibility is available at the Sun-Earth Connection Data Availability Catalog at http://spdf.gsfc.nasa.gov/SPD.html and archived data can be accessed via the NSSDC Master Catalog at the following URLs:
http://nssdc.gsfc.nasa.gov/nmc/tmp/1977-084A.html
http://nssdc.gsfc.nasa.gov/nmc/tmp/1977-076A.html
In addition, a list of URL's, which point to science data, including at the investigators' home institutions, is located at the JPL Voyager web site at http://voyager.jpl.nasa.gov/science/Voyager_Science_Data.html

Budget

Since the beginning of the Voyager Interstellar Mission, the project has continually adapted its operations concept and workforce in response to changes in funding levels. The project has gone from multiple specialized teams to a single operations team wherein each member performs multiple tasks. In response to a NASA request in 1999, the Project Office studied ways to further reduce costs. Benchmarks against other "low cost operations" missions were conducted and it was found that much of what they did was adapted from the Voyager approach and, when all costs were accounted for, Voyager, operating two spacecraft, was comparable to the benchmarked missions in terms of workforce and cost. Nevertheless, in 2002-2003, the flight team was further reduced due to budget constraints. As a result, the current flight team consists of about 9 full-time equivalents. An independent review by an advisory group convened by the Director for Astronomy and Physics at JPL concluded that workforce below this level would result in unacceptable risks. The guideline budget would continue operations at the current minimum level. It includes the costs to support the minimum flight team described above as well as a low level of project management.

Concurrent to the reductions in the flight team in 2002 were reductions in the level of funding for science data processing, analysis and archiving. Because of the minimum level of funding, there has been a reduction in the number of graduate students and post-docs supporting the project, and the co-investigators are now performing much of the data processing and validation. The guideline budget includes costs for science center functions related to operating the instruments and performing quick-look data processing. Also included are limited science analyses required to ensure proper instrument operations and the validity of the data before they are archived. Science data analysis funds allow for limited science analysis and the publication and presentation of select papers, primarily of major science events.

The proposed optimal science budget provides for limited increases in science center functions and enhanced science data analysis functionality. Some of the benefits from this increased budget:

- Enable all experimenters a somewhat more in-depth analysis of science data than that afforded in the guideline budget.
- Increase participation of undergraduate and graduate students in customized data processing and analysis. An additional benefit would be the introduction of younger scientists into the space physics community.
- Perform computer simulations of LECP responses to minor ion species and non-radial plasma flows so as to improve understanding of bulk flow velocities in the heliosheath, Document the results and include on-line as technical reports.
- Analyze the full spectra of plasma data in the low-density regions. Currently, only a subset of the data have been analyzed by hand when need.
- Obtain more reliable flow angles by using monthly calibrations to derive a correction factor for the B-cup data. More reliable data in this cup will reduce velocity uncertainties.
- Recent work has shown the value of alpha enhancements in tracing CME ejecta through the heliosphere. Since alpha densities are very low in the outer heliosphere, the data are difficult to extract from the noise. But since the alpha signal is a fixed energy multiple above the proton peak, we can use this relation to develop an averaging scheme to extract the He parameters.
- Provide for more comparisons of solar wind features in the inner and outer heliosphere to understand the solar wind evolution.

In operations, the optimal budget would provide for an increase in system administration support beginning in FY04 to allow Voyager to become up to date with AMMOS deliveries and remain in step with other missions. Estimated cost is about 0.25 FTE per year. In addition, one time investments would allow for risk reductions as outlined below:

- Development of a temperature estimation tool would alleviate need for outside consultation and the attendant costs and allows the team to make decisions about optimum and/or safe thermal balance when reconfigurations due to decline in power become necessary. A one-time investment of $60K in 2004 is proposed.
- Updates to sequence generation software to allow Voyager specific software to interface with upgrades in DSN and AMMOS software. Estimated cost is about $75K in FY04.

Costs for Deep Space Network Support and in-kind support by the Advanced Multi-mission Operations System, which are not included in the project's budget are included in Table III of Appendix 1. These are based on approximately 10 hours of coverage per day per spacecraft, using both 34-meter and the higher cost 70-meter antenna. Other NASA-provided support, not included in the Voyager budget, support science teams at the GSFC and are also included in Table III. Data services charged to the Voyager budget are included in Item 2a of Tables I and II.

Voyager is the only mission currently exploring the far outer heliosphere. The spacecraft are capable of continued operations and are in position *now* to characterize the Sun's influence far away from the source. Until there are other missions to the outer heliosphere, Voyager will provide unique in situ information about this region of space beyond 90 AU. Voyager 1 is poised to encounter the termination shock within the next few years. Continuation of the mission at the optimal level would allow for a more robust science mission that would answer fundamental questions about solar influences in the distant heliosphere and the interactions between the solar and interstellar media.